An Autonomous Mobile Platform for Underway Surface Carbon Measurements in Open-Ocean and Coastal Waters

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***Abstract* - The NOAA Pacific Marine Environmental Laboratory and Liquid Robotics, Inc., are collaborating to address an urgent need for long-term *in-situ* observation of carbon parameters over broad swathes of the global coastal and open ocean by integrating a suite of state-of-the-art pCO_2, pH, and CTD sensors onto a Wave Glider wave-propelled autonomous marine vehicle (AMV). The resulting Biogeochemical Wave Glider will be capable both of acting as a long-duration (up to 1 year) "virtual mooring" to augment the existing sparse collection of moored carbon science sensors and of conducting autonomous, basin-scale ocean transits to provide new insight into the spatial variability of carbon uptake and associated parameters.**

I. Introduction

Understanding the role of anthropogenic carbon as a forcing factor in global climate change is an important scientific goal that has far reaching implications for government policy formulation with associated impacts upon social and economic activities and infrastructures. The presence of excess green-house gases in the atmosphere is fundamentally tied to the uptake of carbon by the world's oceans. The ocean stores carbon primarily in the form of dissolved inorganic carbon, which is increasing with time due to the absorption of CO_2 gas from the atmosphere. Greater understanding of the global ocean's ultimate capacity as a sink of anthropogenic carbon is much needed.

In this paper we describe an internally funded prototype development project to integrate a suite of existing state-of-the-art pCO_2, *p*H, and CTD sensors onto the existing Wave Glider autonomous marine vehicle (AMV). Liquid Robotics, Inc. (LRI) is responsible for the Wave Glider AMV and integration and operations support and the NOAA Pacific Marine Environmental Laboratory (PMEL) is providing the $MAPCO_2$ sensor and sensor suite repackaging and integration expertise. While the primary payloads, the $MAPCO_2$ and pH sensors, and the mobile platform, the Wave Glider, are the products of relatively recent development efforts, they have both been extensively tested and deployed for extended periods at sea. When completed, the Biogeochemical Wave Glider package will operate in a similar manner to the current network of CO_2-measuring ships of opportunity (SOOP), but with the distinct advantage that the Wave Glider can be specifically directed to sample in areas outside of the normal shipping lanes where we are currently unable to collect the data needed to properly assess the global air-sea CO_2 flux. The notional ocean testing program will address fundamental questions in ocean carbon chemistry through a sequence of trials that will also allow us to assess the durability of the package.

The major achievements expected from this initial effort will be the development and testing of a persistent, mobile, and autonomous ocean platform that is capable of making extended voyages to measure carbon and other physical properties in the ocean. The long-term goal of this effort is to provide a useful new technology to the ocean science community for making surface underway measurements. Use of this vehicle could lead to a new paradigm for economical underway surface observations that does not rely on expensive research ships and is not restricted to the standard shipping lanes of volunteer vessels. The notional sea trial and survey deployments would test not only the technology, but would also contribute valuable scientific data that would help improve our understanding of the spatiotemporal variability of CO_2 and would yield new insight into the process-level factors controlling CO_2 sources and sinks in open-ocean and coastal waters. The notional deployment program would also make a significant contribution to our knowledge of the extent of ocean acidification in US coastal waters.

This paper begins with an overview of ocean carbon science observational deficiencies, providing the motivating background for our prototype development effort. We then discuss three enabling technologies that are being brought together to create the

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Biogeochemical Wave Glider system. Next, we describe the development of the payload suite and the integration of this new payload onto the Wave Glider platform. We conclude with a proposal to test the Biogeochemical Wave Glider in both open ocean and coastal environments, including validation of the system against buoy- and ship-borne sensors.

II. OCEAN CARBON SCIENCE BACKGROUND AND MOTIVATION

The time and space scales of variability in surface water CO_2 concentrations make it challenging to evaluate global fluxes based on *in situ* measurements alone. The latest global flux climatology, based on approximately three million measurements collected between 1970 and 2007, gives a net ocean uptake of 1.4 ± 0.7 Pg-C yr^{-1}, Takahashi et al. [1]. Gruber et al. [2] analyzed modern oceanic uptake rates of anthropogenic CO_2 for a wide variety of approaches including observations (sea-air CO_2 partial pressure difference (ΔpCO_2), sea-air ^{13}C disequilibrium and atmospheric O_2/N_2) and models (ocean data inversion, atmospheric data inversion, and ocean general circulation/biogeochemical models). They found that these different approaches, including the Takahashi climatologies, are consistent within their uncertainties (ranging from 1.5±0.9 to 2.4±0.5 Pg-C yr^{-1}), but the uncertainties on all these approaches are still quite large. A range of nearly 1 Pg-C yr^{-1} is simply insufficient for producing a reliable global carbon budget or for predicting how the ocean carbon sink is changing over time-scales relevant to policy and management decisions (i.e. <10 years). Improved estimates of ocean carbon uptake are needed.

A. Open-Ocean Carbon Data Limitations

A full understanding of air-sea CO_2 fluxes is not currently possible due to a lack of seasonal and geographic coverage of ΔpCO_2 measurements, and an incomplete understanding of factors controlling air-sea CO_2 exchange. The Takahashi et al. dataset [1], Fig. 1, shows large regions of the ocean that still have no carbon measurements after 40 years of observations (white regions in Fig. 1). Most of the global ocean has been observed for <3 months of the year, making it nearly impossible to characterize the seasonal cycle. Most CO_2 measurements have been made on research ships, which have very limited coverage of the global ocean and very few seasonal repeats. In recent years, research ships have been supplemented by installing CO_2 systems on commercial ships referred to as ships of opportunity (SOOP). The yellow to red regions of good seasonal coverage in Fig. 1 are from SOOP lines, but they are generally restricted to standard shipping lanes in the northern hemisphere. It is nearly impossible to collect regular measurements outside of these routes.

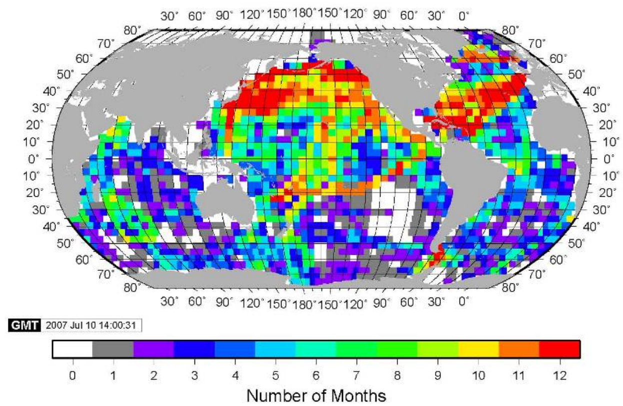

Fig. 1 Number of months with observations for each 4° x 5° grid cell (Takahashi et al., 2009)

B. Coastal Ocean Carbon Data Limitations

Another limitation of the global CO_2 climatology is that it explicitly excludes continental margins, which are characterized by much higher spatial and temporal variability in the direction and magnitude of air-sea CO_2 exchange than the open ocean (e.g. Borges [3], Hales et al. [4], and Cai et al. [5]). The large carbon fluxes occurring within or passing through the coastal oceans are of great importance for accurately quantifying the carbon budgets of the bordering open-ocean, atmospheric, and terrestrial regions. Furthermore, coastal carbon dynamics are highly sensitive to changing wind patterns, river runoff, and upwelling dynamics. Consequently, coastal carbon fluxes can change rapidly from being a carbon source to a carbon sink. To date, air-sea carbon fluxes from North American continental margin (NACM) waters have been so poorly sampled that uncertainty remains as to whether these regions are net sources or sinks for CO_2 (e.g. Doney et al. [6] and Chavez et al. [7]). The most recent synthetic effort, Chavez et al. [7], suggests that NACM waters collectively act as a weak source of 1.6 ± 36 Tg-C yr^{-1} to the atmosphere, with uncertainties over 20-fold higher than the mean. The total flux is the sum of very large CO_2 sources at low latitudes on the Pacific and Atlantic coasts and in the Gulf of Mexico (44.9 ± 14 Tg-C yr^{-1}), balanced by nearly equivalent sinks in mid-high latitude Pacific and Atlantic continental margins. However, the paucity of observations in regions contributing to the large local CO_2 fluxes (e.g. Gulf of Mexico, Gulf of Alaska) lead to ambiguity in the continent-scale integrated total annual flux. Fig. 2 shows that only a few regions contain observations in all 12 calendar months, and that the average observational coverage is slightly less than three months

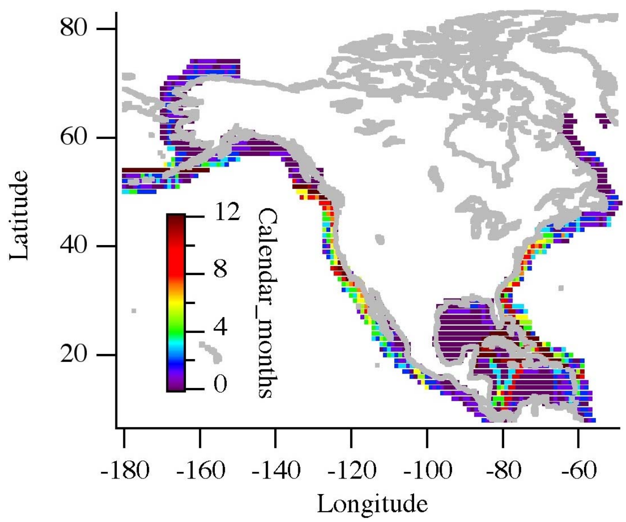

Fig. 2 Number of months with observations in the North American Continental Margins, 1° x 1° grid.

per pixel. The high flux regions are disproportionately under sampled. This low data density calls into question a synthesis as reliant on extrapolation as that in the Chavez et al. [7] assessment.

C. Ocean Acidification

Ocean acidification is a global phenomenon that has received a great deal of recent attention. As CO_2 is absorbed into the ocean, it reacts with water to form carbonic acid, increasing ocean acidity. Since industrialization began, surface-ocean acidity has increased by 30%. This ongoing ocean acidification has the potential to affect calcification, reproduction, behavior, and growth of marine organisms, Doney et al. [8]. However, most of the focus thus far has been on the long term *p*H trends. Measurements of *p*H on a PMEL mooring at station PAPA in the Gulf of Alaska show a seasonal range of more than 0.1 *p*H unit (unpublished data), the same size as the estimated total change in *p*H over the last 200 years. A better understanding of ocean *p*H temporal variability is needed to fully understand ocean acidification.

A recent North American Carbon Program (NACP) coastal research cruise off the northern California coast in May–June 2007 observed upwelling of anthropogenically “acidified” waters, Feely et al. [9]. These “acidified” waters had pH values <7.75 and that dissolution of aragonite was thermodynamically favored over precipitation (or preservation). Sea surface pCO_2 values observed between British Columbia and Baja California during the cruise showed a large range (200-800 μatm). The highest pCO_2 values were strongly correlated with the lowest sea surface temperatures indicating that upwelling of CO_2-rich waters was responsible for the unusually low *p*H, corrosive waters. Recent underway pCO_2 measurements on NOAA coastal fisheries vessels have expanded the spatial and temporal range of observations along the Pacific North American margin. Measurements along the US west coast during the summer and early fall of 2007 revealed even higher pCO_2 values off the central California coast (~1020 μatm) than seen during the NACP cruise, suggesting that acidified waters may be more widespread than observed during the cruise, [9]. More observations are needed to understand the link between anthropogenic CO_2, upwelling and ocean acidification.

III. ENABLING TECHNOLOGIES

A. $MAPCO_2$

Since December 1996, the Monterey Bay Aquarium Research Institute (MBARI) has maintained bio-optical and chemical instrumentation on two moorings in the Equatorial Pacific in collaboration with NOAA/PMEL. As part of this project, MBARI developed an autonomous pCO_2 system based on an infra-red analyzer and bubble type equilibrator. In 2003, PMEL engineers worked with the MBARI group to take a similar MBARI designed pCO_2 system for a drifting buoy and modify it to work as a buoy based system (referred to hereafter as the $MAPCO_2$ system). One major modification was the addition of a NOAA/ESRL certified standard gas that would allow the system to recalibrate autonomously in the field. In 2004, the moored CO_2 project was picked up by NOAA’s Office of Climate Observations to begin developing a global array of moored CO_2 systems as part of the ocean observing system for climate. PMEL currently maintains 19 moored CO_2 systems in the Pacific and Atlantic Oceans, Fig. 3. The system is designed for a nominal deployment life of 400 days with measurements every three hours and data transmissions once per day. The long-term goal is to populate the network of OCEAN Sustained Interdisciplinary Timeseries Environment observation System (OceanSITES), [10], so that CO_2 fluxes will become a standard part of the global flux mooring network. Additional information about the moored pCO_2 program can be found in [11] and [12].

The $MAPCO_2$ system is both reliable and accurate. In 2006 an underway pCO_2 system was added to the *R/V Atlantic Explorer*. This ship passes very close to the Bermuda Testbed Mooring (BTM) with a $MAPCO_2$ system on at least a monthly basis allowing regular comparisons of the moored and shipboard CO_2 data, Fig. 4 An analysis of the moored and shipboard data showed that the two systems agreed to within 0.5±4.7 μatm (n=15,462) when the ship was within 10km of the mooring and the time was within 3 minutes. By comparing data over a range of distances one can begin to assess the correlation length scales for the region. Preliminary analysis at BTM suggests that data are coherent within about 80 km regardless of season.

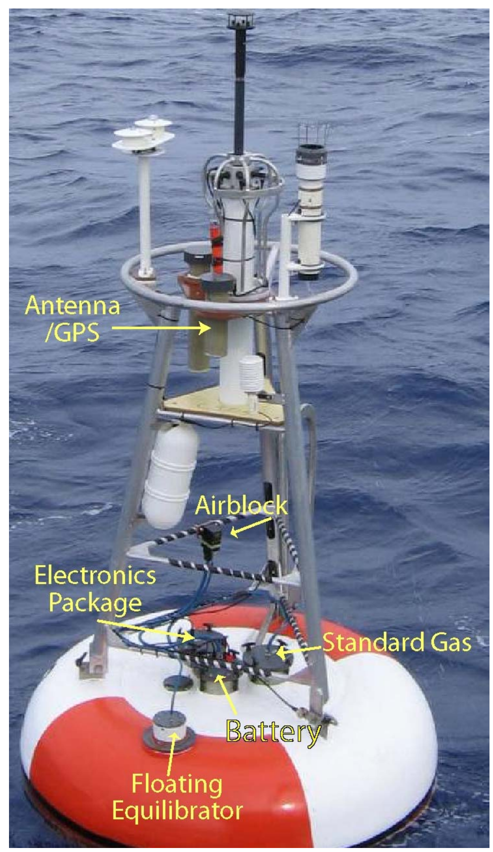

Fig. 3 The $MAPCO_2$ system installed on a buoy.

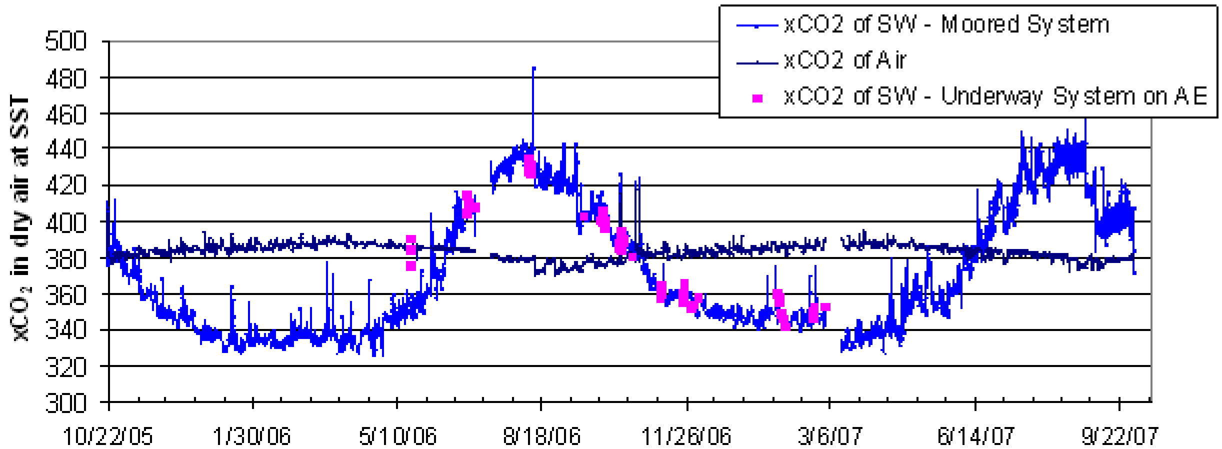

Fig. 4 Comparison of time-series CO_2 measurements from the Bermuda mooring and the underway system aboard the *R/V Atlantic Explorer*.

B. pH Sensor System

Martz and Johnson [13] explored the use of a Honeywell Durafet® ISFET sensor for seawater pH measurements over sustained periods *in situ*. They demonstrated that off-the-shelf Durafet sensors could operate for months without calibration in shipboard laboratories and moorings in the surface ocean. In July 2007, following a month-long test tank experiment to validate the accuracy, stability, and durability of the system, the Durafet-based sensor was installed on the *R/V Western Flyer* for a survey cruise off-shore. A very tight relationship was observed between the *p*H and underway pCO_2 systems over the entire cruise from Monterey Bay offshore beyond the California current. The ISFET showed no degradation in performance over a range of pH, temperature, and salinity values (pH = 7.9-8.3; temp = 12-20°C; salinity = 32.4-33.8). An autonomous version of the Durafet was deployed for one month in the surface ocean on the MBARI L01 mooring, located at the mouth of the Elkhorn Slough estuary, Jannasch et al. [14] Elkhorn Slough is a high fouling environment and the sensor was deployed without any protection from biofouling. Despite the extreme variability of the estuary conditions, however, the sensor functioned well for the duration of the deployment.

The compact size and low power requirements of the Durafet® ISFET sensor make it ideal for integration into our vehicle. Including a second carbon parameter as part of the package will allow us to address a much broader range of questions about the carbon chemistry of the waters including the changes in ocean acidification.

C. The Wave Glider Autonomous Marine Vehicle

The Wave Glider is a new class of wave-propelled, persistent ocean vehicle, Fig. 5. Roger Hine, the lead inventor of the vehicle and the CEO of Liquid Robotics, began work on the Wave Glider vehicle in 2005 with a vision to enable new types of ocean observation that do not require costly deep-water moorings or ship operations. Encouraged by immediate success with initial prototype designs, Mr. Hine and several colleagues founded Liquid Robotics, Inc. in 2007 to further develop the platform for scientific, commercial, and military applications. Since that time, engineering prototypes and the first product generation of the Wave Glider vehicles have logged a combined total of more than 42,000 nautical miles at sea, with the longest continuous mission lasting more than eight months (mission currently on-going). Table I gives an overview of the characteristics, capabilities, and features of the latest (third) generation of the Wave Glider vehicle.

Fig. 5 The Wave Glider AMV harnesses wave energy for propulsion, decoupling platform endurance from battery or chemical energy storage systems. The Wave Glider is able to maintain headway on its desired course in calm seas and independent of wave direction.

The Wave Glider represents an innovative approach to ocean persistent presence; it harnesses ocean wave energy to provide essentially limitless propulsion while solar panels continually replenish the batteries used to power the Wave Glider's control electronics and payload systems. The Wave Glider vehicle is propelled by the purely mechanical conversion of ocean wave energy into forward thrust, independent of wave direction. Just as an airplane's forward motion through the air allows its wings to create an upward lifting force, the submerged glider's vertical motion through the comparatively still waters at the glider's depth allows its wings to

convert a portion of this upward motion into a forward propulsion force. As waves pass by on the surface, the submerged glider acts a tug, pulling the surface float along a predetermined course.

Through extensive engineering trials and demonstrations, the Wave Glider's capability for long-term autonomous operation in the open and coastal oceans has been firmly established. For example, the Wave Glider has successfully circumnavigated the Big Island of Hawaii and surveyed down the California coast from Monterey Bay to San Diego, with an average speed over ground of 1.5 kts in both of these missions. Ref [15] gives a more detailed description of the Wave Glider, its capabilities, and its performance under a variety of ocean conditions.

TABLE I

CHARACTERISTICS AND CAPABILITIES OF THE WAVE GLIDER VEHICLE

Physical Characteristics	
Vehicle Configuration	Submerged glider connected to a surface float by a tether.
Dimensions	Float: 82" x 23.5"; Glider: 15.7" x 75.1"; Wings: 42.2" wide
Weight and Buoyancy	75 kg mass, 150 kg displacement
Endurance	Up to 1 year
Capabilities and Functionality	
Propulsion Power	Mechanical conversion of wave energy into forward propulsion.
Speed through Water	>0.5 kt in Sea State 1 (SS1); >1.5 kt in Sea State 3 (SS3).
Battery	86W (peak) solar panel charging a 650 Wh Li-ion battery pack.
Payload Power Available	10 W continuous (typical), depending upon latitude, weather, etc.
Communications Systems	Iridium Satellite Modem. RF Modem
Navigation Systems	12 Channel, WAAS enabled GPS; Compass; Water Speed (Optional)
Control Interfaces	Web-based, GUI Chart interface, with location and status indicators.
Proven Survivability	SS6 (WMO) (14-18ft seas, 30-40kt winds)
Emergency Location Devices	Light and RF beacon. Optional acoustic beacon.

IV. PROTOTYPE BIOGEOCHEMICAL WAVE GLIDER DEVELOPMENT

Table II gives an overview of the science sensors that will be integrated onto the Wave Glider vehicle. The MAPCO_2 technology is being adapted to work in the Wave Glider as an autonomous underway CO_2 sensor. NOAA/PMEL is responsible for repackaging the existing MAPCO2, pH, and conductivity-temperature-depth (CTD) sensors into the form-factor of the Wave Glider payload bays. The MAPCO_2 sensor is larger and more complex than the *p*H and CTD sensors. Repackaging the MAPCO_2 components to fit the form-factor of the Wave Glider payload bays comprises the bulk of NOAA/PMEL engineering efforts. Fig. 6 shows the notional positioning of the components of the MAPCO_2 sensor within the Wave Glider. As part of this project, NOAA/PMEL is exploring ways to make the MAPCO_2 system more efficient, such as testing alternative equilibrator designs that are smaller and faster. These alternative equilibrators can take advantage of the forward motion of the vehicle to create a water flow without the power requirements for pumping water. A shorter equilibration time would lower the total power consumption of the MAPCO_2 sensor. Finally, NOAA/PMEL is providing a payload microcontroller to coordinate sensor measurements times, to communicate with each sensor via serial ports, and to record each sensors' data. The Wave Glider provides conditioned power to the NOAA/PMEL payload, which otherwise operates independently of the Wave Glider.

LRI is responsible for the mechanical, electrical, and software integration of the Biogeochemical payload suite onto the Wave Glider. LRI is working closely with NOAA/PMEL to make minor modifications to the Wave Glider design as needed to accommodate the unique requirements of the MAPCO_2 and *p*H sensors. LRI is creating new payload interface software to allow the Wave Glider's command and control module to execute supervisory control over the payload package. The Wave Glider will communicate with the payload package via a serial line and will control the power to the sensor. The Wave Glider will transmit portions of the payload data over its existing Iridium communications link and will also provide a payload data storage system. Operators and science users will have access to the payload data via LRI's web-based operator interface. LRI and NOAA/PMEL are jointly responsible for all bench testing, sensor calibration and characterization, and engineering sea trials. The Wave Glider's modular payload architecture facilitates bench and integration testing. Dock-side in-water tests will be conducted at LRI's Kawaihae Harbor facility, and operational sea trials will be conducted in LRI's test range offshore of Puako, HI.

TABLE II

THE WAVE GLIDER BIOGEOCHEMICALSENSOR SUITE. CTD UNCALIBRATED RANGES AND ACCURACIES IN PARENTHESES.

Supplier	Sensor	Measurement	Calibrated Range & Accuracy
NOAA PMEL	MAPCO_2	pCO_2 SW & Air (ppm)	200 to 600 ± 3 (stable over ~year)
Scripps (Martz)	custom pH	SW Acidity (*p*H)	0 to 14 ± 0.01 (±0.005 stability ~wks)
Seabird Electronics	Glider Payload CTD	Conductivity (S/m)	0 to 6 ± 0.0003 (0 to 9 ± 0.0010)
		Temperature (°C)	1 to 32 ± 0.002 (-5 to +45 ± 0.010)
		Pressure (dbar)	0 to 100 ± 0.1% FS (same)
		Salinity (PSS 78)	0 to 35 ± 0.005 (0 to 45 ± 0.015)

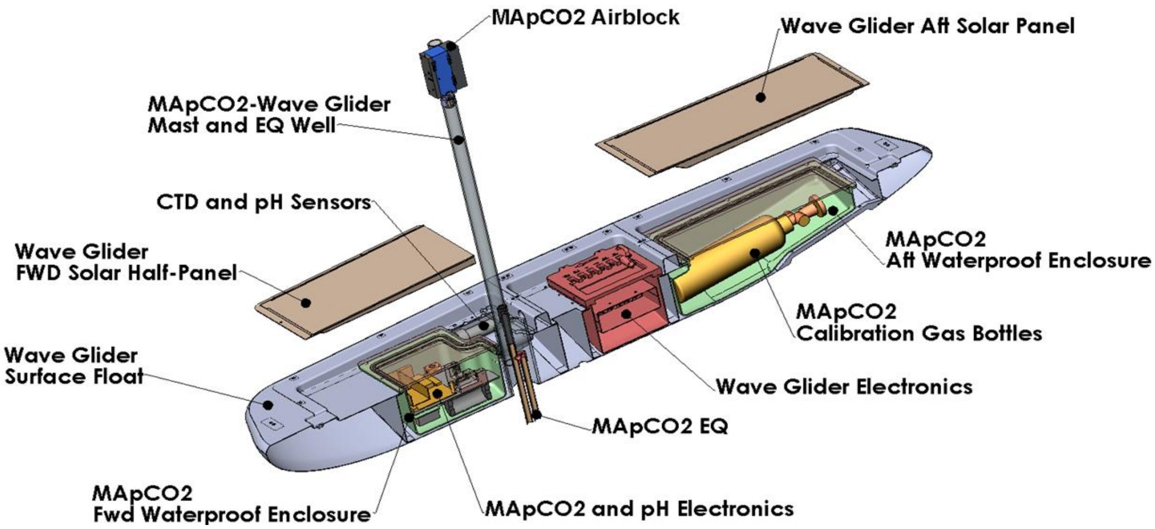

Fig. 6 Integration of the Biogeochemical payload sensor suite onto the Wave Glider vehicle.

V. NOTIONAL SEA TRIALS AND DATA COLLECTION PROGRAM

Once the scientific sensors have been integrated into the Wave Glider vehicle and undergone testing under local conditions, the package will need to be tested on longer voyages and under a variety of oceans conditions. In this section, we propose an (unfunded) initial ocean testing program that would allow us to assess the durability of the package through a sequence of coastal and open ocean sea trials. The data collected in these trials would also allow us to address fundamental questions in ocean carbon chemistry.

A. Open-Ocean System Tests

The first extended test of the Biogeochemical Wave Glider would be to conduct one or more transect(s) from Kaneohe Bay, Oahu, HI to the Hawaii Ocean Time series station ALOHA and back. Fig. 7 shows the proposed path (yellow line) the Wave Glider would take. The red dots on the map show the locations of $MAPCO_2$ moorings in the area. The transect would start in Kaneohe Bay very near the CRIMP $MAPCO_2$ mooring, allowing a comparison between the initial readings from the Wave Glider sensors and the data coming from the same type of sensors installed on the mooring. In addition to the moored data, discrete samples would be collected for the full suite of parameters measured by the Wave Glider. The Wave Glider would first run parallel to the windward shore of Oahu to sample the coastal conditions near the island. From the North Shore, the Wave Glider would proceed to the WHOTS mooring located approximately 120 km to the North where it would sample open ocean oligotrophic gyre conditions. The WHOTS mooring also has a $MAPCO_2$ system that can be used to validate the Wave Glider data at the half way point of the transect. The WHOTS buoy is located at the Hawaii Ocean Time-series site, Station ALOHA. Station ALOHA is visited monthly and sampled for a wide array of physical and biogeochemical parameters over about a 5 day period (shown in green on the map). The timing of the Wave Glider transect(s) would be coordinated with the HOT cruises to provide the maximum overlap for validation with the shipboard measurements. After circling the WHOTS mooring, the Wave Glider would follow the same path back to Kaneohe Bay where it could be checked against the CRIMP mooring data and discrete samples collected when the vehicle is retrieved. The total track length would be approximately 290km. Since the variability in most properties is much smaller in this region of the North Pacific compared to many other locations in the global ocean, this would give us a good test of the stability of the sensors under open ocean conditions.

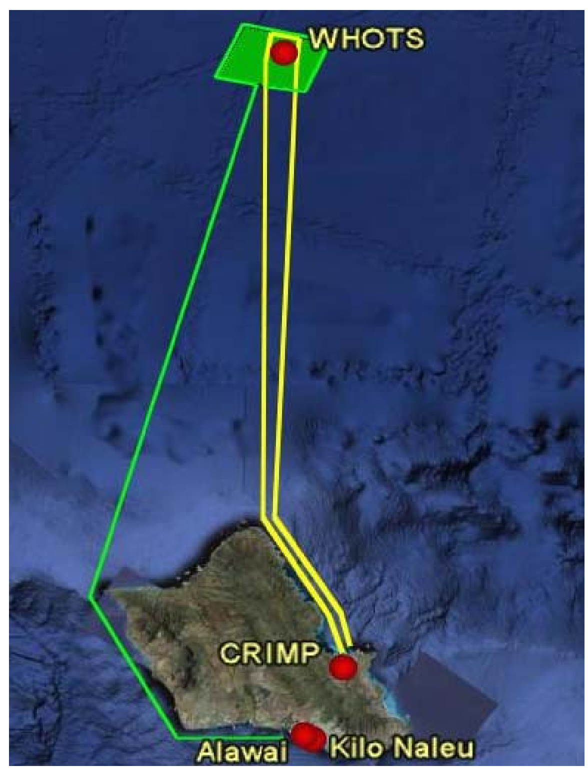

Fig. 7 Wave Glider will execute an autonomous mission (yellow lines) to the WHOTS buoy deployed approximately 120 km north of Oahu, HI. This mission will overlap with one of the regularly scheduled (monthly) HOT cruises (green line), allowing sensor validation data to be collected at the WHOTS buoy and aboard ship.

B. Coastal-Ocean System Tests

After one or more successful transits to Station ALOHA, the Wave Glider would need to be tested on a longer voyage in a more dynamic area. We propose to conduct such a test starting in Puget Sound near Seattle, WA and transiting down the west coast to San Diego, CA (Fig. 8, yellow line). We anticipate running the Wave Glider along the 120-140m isobaths which should be far enough off-shore to avoid most of the coastal boat traffic, but still be in-shore of the major shipping lanes. This region of the continental shelf is known for seasonal upwelling which has been recently shown to bring acidified offshore waters up onto the shelf, [9]. The Wave Glider cruise would be scheduled for the summer to capture this upwelling signature.

The proposed path would take the Wave Glider past several moorings ($MAPCO_2$ systems shown in red; other CO_2 systems shown in green) allowing additional validation of the sensors during the transit. NOAA/PMEL operates two underway pCO_2 systems on coastal NOAA fisheries vessels that could also be used to validate the Wave Glider readings where their cruise paths cross. Finally, NOAA also periodically runs survey cruises along the west coast measuring a wide suite of physical, geochemical and biological parameters. Every effort would be made to coordinate the Wave Glider test to coincide with the NOAA West Coast survey cruise.

Fig. 8 In Year 3 of the project, a second Wave Glider will execute an extended (>2000 km) autonomous mission (yellow line) to measure coastal carbon chemistry parameters along the west coast of the US.

VI. CONCLUSIONS

We have described a prototype development effort to integrate a suite of existing state-of-the-art carbon science sensors onto the Wave Glider, a persistent, mobile, and autonomous marine vehicle. The ultimate goal of the present effort is to gain a better understanding of ocean carbon chemistry and ocean acidification through a focused ocean measurement program that combines existing state-of-the-art sensors with an existing wave-propelled autonomous sea surface vehicle. While the primary payload, the $MAPCO_2$ sensor, and the mobile platform, the Wave Glider, are the products of relatively recent development efforts, they have both been extensively tested and deployed for extended periods at sea. The immediate focus of our efforts is the integration of these two capabilities and subsequent testing and demonstration in an abbreviated sea trials program. The prototype Biogeochemical Wave Glider will collect a variety of physical and chemical measurements to help interpret the measured variability in surface water and atmospheric pCO_2. The use of an autonomous vehicle will improve our ability to collect surface carbon data on time and space scales that are currently cost prohibitive using conventional ship-board techniques. Data will be transmitted back to the laboratory in near-real time. If the vehicle passes through an anomalous region along the coast, the operating scientists will be able to redirect the Wave Glider to survey that region more extensively. This flexibility will significantly enhance our ability to study and understand the dynamics of the coastal regions. The measurement of two carbon parameters will allow us to evaluate the full carbonate system and better understand how ocean acidification is developing in the open ocean and along our coasts. The correlation between the carbonate parameters and the physical properties of the waters may allow us to use satellites to examine the large scale spatial patterns of ocean acidification and how physical processes may be influencing those patterns.

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